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LANL

Microwave remote sensing for atmospheric chemistry

Trip report: IAP, Bern and NRL, DC

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Background

Microwave remote sensing is a well-established technique for making sensitive thermal emission measurements at microwave frequencies. This thermal emission described by Planck's law is the electromagnetic radiation at microwave wavelengths intrinsically emitted from hot objects. This is the blackbody radiation that constitutes the microwave baseline signal. The transitions between quantized rotational states of the constituent gas species gives rise to spectral features on top of this background signal. A distribution of the atmospheric constituents is retrieved from the measured emission lineshape correlated to pressure broadening as a function of altitude. Thus microwave radiometers enable the detection and continuous monitoring of trace gases present in the atmosphere. Microwave radiometers are deployed at various sites around the world measuring an assortment of species and meteorological parameters of interest. Several groups worldwide are active in this field, NRL remote sensing division and the Institute of Physics at the University of Bern among the prominent few. The technology is quite mature with the availability of room temperature RF components at W–band frequencies.

The microwave remote sensing technique provides information that complements other methods of remote sensing. Microwaves have the ability to penetrate clouds and are not heavily impacted by rain due to the long wavelengths. As this method uses the thermal emission from the atmosphere, it does not require illumination from the sun. This is an advantage over traditional optical remote sensing methods thus enabling nighttime measurements and under all weather conditions.

There are two types of microwave remote sensors: passive and active. The passive instrument primarily discussed here only detects and records radiant energy without the need for an active source. The active technique uses a microwave source tuned to excite the species of interest. This is reminiscent of a radar type system applied to spectroscopy.

Passive techniques are widely used for atmospheric observations. For example passive microwave remote sensing of the atmosphere deals with the measurement of the brightness temperature of key trace gases with emission lines in the microwave region of the EM spectrum (300 MHz to 300 GHz). Airborne radiometers sense the temperature of the surface of the earth. Ground-based, upward looking radiometers can measure atmospheric radiance. The signal of interest for passive radiometry is at instrument noise levels ($P = kTB$) and hence demands very sensitive circuitry.

The applications of microwave radiometers are not limited to the atmosphere. Other microwave radiometers measure soil moisture, vegetation, temperature, humidity, sea ice and other surface properties. Typically the radiometers that measure surface properties are at lower RF frequencies than the radiometers that measure atmospheric variables. Several of these remote sensing instruments are part of the international Network for the Detection of Atmospheric Composition Change (NDACC) coordinated by the NOAA [1].

The atmosphere is selectively transparent at certain frequency intervals or windows as shown in fig. 1 and are observable using ground-based sensors. The primary molecules responsible for attenuation of microwave radiation are H_2O and O_2 present in the atmosphere. Figure 1 plots the atmospheric attenuation or optical depth of solar radiation for the entire EM spectrum. There is atmospheric transmission both at ~ 10 µm IR wavelengths and at W-band (1-10 mm wavelengths), indicating both wavelength regions can be used for atmospheric spectroscopy [2].

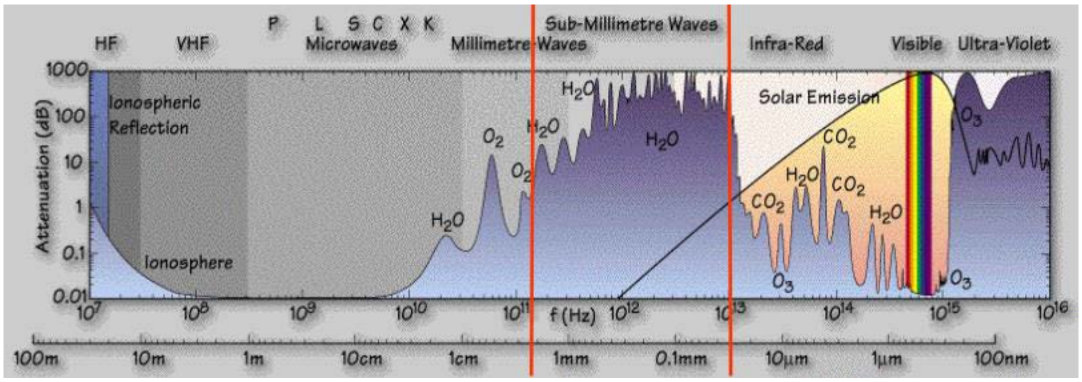


Figure 1: Atmospheric opacity for a "standard" atmosphere (zenith attenuation), showing that there is transmission both at IR and mm wavelengths but very little at THz frequencies. The zenith attenuation at Los Alamos is somewhat lower due to our dry conditions and higher elevation [2].

Gas molecules such as CO, O_3, OH, HO_2, BrO, ClO, and HDO have absorption /emission rotational lines within the W-band (75-110 GHz). It is important to have the ability to remotely monitor these gases' local (i.e., not column integrated) densities for treaty verification and climate-change science. The vast majority of ozone (O_3) is present in the stratosphere between 20 km and 65 km. Stratospheric ozone which has rotational lines in the W-band, plays an important beneficial role in limiting harmful UV radiation, but O_3 in the lower atmosphere is a pollutant and a greenhouse gas. Even though ozone depletion is not a pressing crisis due to the recovery of the ozone hole, there is a continuing need to monitoring long term trends of atmospheric greenhouse gases in order to understand global atmospheric dynamics.

The nature of the incoherent thermal emission detected by a radiometer can be understood by taking into account that any object above temperature T>0 K emits electromagnetic (EM) radiation. This thermal emission intrinsically emitted by objects at non-zero temperature is the blackbody radiation which microwave remote sensing is based upon. A blackbody is an idealized material that absorbs (or emits) all radiation incident on it, at a given wavelength. Planck's law gives the spectral radiance or brightness which is defined as the intensity per frequency per unit area per solid angle from a blackbody in thermodynamic equilibrium and is given as [3]

$$B = \frac{2h\nu^3}{c^2}\left(\frac{1}{e^{h\nu/kT}-1}\right).$$

where ν is the frequency, B is the brightness, h is the Planck's constant, k is the Boltzmann's constant and T is the temperature in K. In the millimeter region of the EM spectrum, the Planck function reduces to a simplified expression $B = \frac{2\nu^2 kT}{c^2}$ following the Rayleigh-Jeans limit, $h\vartheta =$

kT which gives rise to a linear relationship between brightness and temperature. This temperature is known as the brightness temperature. It is common to express the measured radiometric power in terms of the brightness temperature. Note the brightness temperature, T_b is not always equal to the physical temperature T and is related to the physical temperature by the emissivity. For an ideal blackbody, the emissivity e is 1 in that case $T_b = T$.

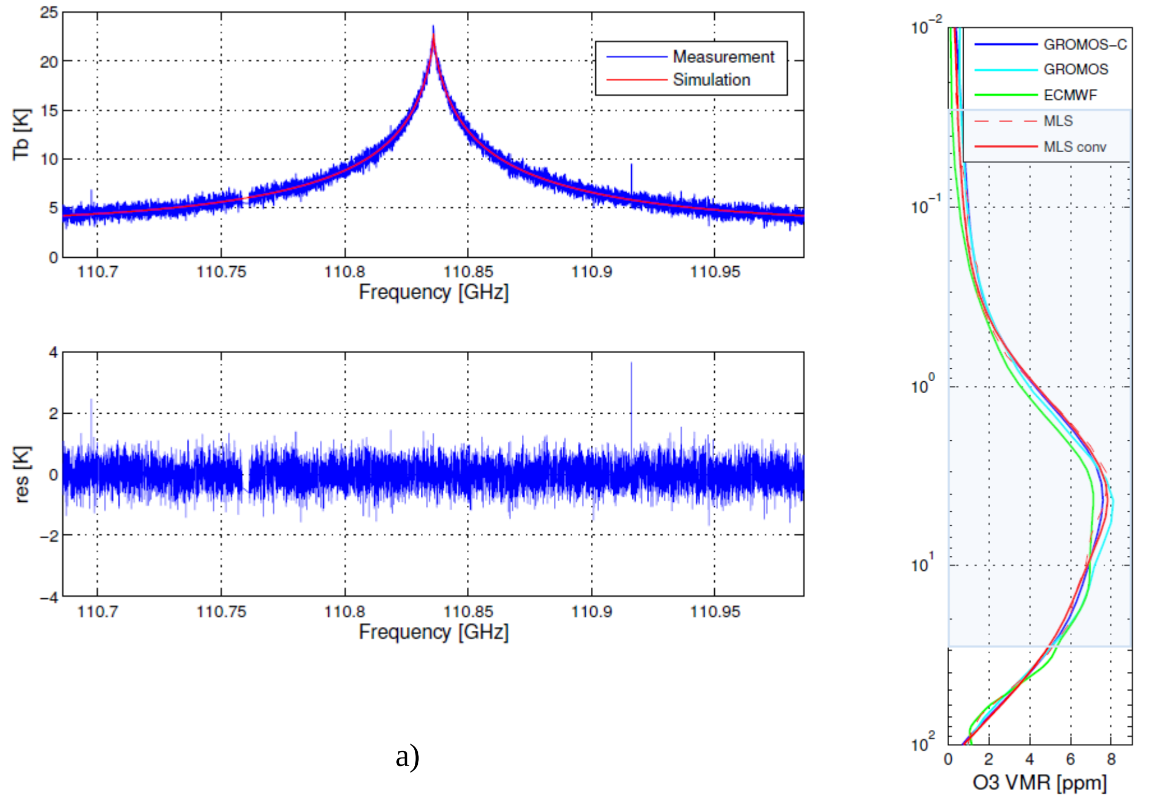
The blackbody produces a continuous spectrum whereas emission spectra produce narrow band peaks relative to the broadband blackbody spectrum. These characteristic emission peaks arise due to the thermal excitation of the rotational energy levels. The collisions between neighboring molecules cause a change in the kinetic energy states. As the energy change involved in these transitions is small (~few meV), the emission occurs at microwave frequencies. These emission spectra are what we are interested in looking at.

Since the radiation signal is noise dominated, radiometers must be very sensitive to be able to detect extremely weak radiation at microwave frequencies. The smallest temperature change, ΔT that can be detected by the radiometer is governed by the radiometer equation, namely $\Delta T = \frac{T_{sys}}{\sqrt{B\tau}}$. where T_{sys} is composed the antenna temperature due to the observed source and the receiver noise temperature which is the contribution due to thermal noise in the receiver electronics, B is the filter bandwidth and τ is the measurement integration time [4,5]. Longer integration times lead to smaller uncertainty in temperature thereby increasing the radiometric resolution.

Current radiometers

While the technology has been around for over 30 years, microwave remote sensing is still a research effort and not commercially available unlike a spectrometer in the optical or NIR.

GROMOS-C [6] developed by the Institute of Physics (IAP) at the University of Bern is a compact, total power radiometer that measures the strong ozone rotational line at 110.86 GHz, primarily built for measurement campaigns at remote sites around the world. These campaigns typically involve relocating the instrument to a remote site and continuously acquiring data for a year or more to generate continuous, long term time series of the targeted trace gas. There are other instruments such as LIDARs, FTS, radiosondes etc. that also participate in the campaign for side-by-side comparison of ozone profiles. Figure 2 shows the measured brightness temperature lineshape and the corresponding vertical profile. As mentioned previously, the vertical profile is derived from the lineshape using an inversion algorithm.



a)

b)

Fig.2 a) Measured lineshape from GROMOS-C b) A comparison of the vertical profile with MLS, GROMOS and ECMWF. Figures are reproduced from [6].

In addition to the ozone radiometers, GROMOS and GROMOS_C, IAP Bern has built and maintains a suite of radiometers that measure concentration of water vapor at 22 GHz. MIAWARA and MIAWARA-C are both ground based water vapor radiometers that measure long term changes in water vapor abundances in the middle atmosphere. MIAWARA resides in the observatory at Zimmerwald near Bern whereas MIAWARA-C [7] is the compact campaign version of MIAWARA. The instrument uses a hot-cold calibration technique, described later, with liquid nitrogen (LN2) as the cold target.

IAP has also developed wind radiometers, WIRA and WIRA-C [8] that measure stratospheric winds as high as 100m/s. By using the Doppler shifts due to the ozone molecules in motion, horizontal speeds are measured by observing the strong rotational line of Ozone at 142 GHz. Frequency and temperature stabilization are extremely critical due to the measured Doppler shifts on the order of a few KHz. WIRA-C is the more modern and compact version of WIRA primarily operated during campaigns. WIRA-C uses USRP X310 as the backend spectrometer.

During my site visit to IAP, Bern, I was able to see the GROMOS, WIRA-C and MIAWARA radiometers and interact with Dr. Axel Murk who is the head of the Terahertz and optics group. He has been intimately involved with the development of GROMOS-C. I have been communicating with him over the past year. As a world expert on radiometers, he has provided guidance and feedback for developing microwave remote sensing capability at LANL. This visit overlapped with another radiometry expert from the Naval Research Laboratory (NRL), Washington DC, Mike Gomez's visit to Bern to test and characterize MOPI5, a room temperature 110 GHz ozone receiver collaboratively built by NRL and Bern. This was a unique opportunity to capture firsthand experience in order to bring these technical capabilities back to LANL and to forge long lasting ties within the community in this remote sensing field. I interacted with the students and post-docs at IAP Bern

An alternative approach used by the group at Chalmers University, Sweden is a compact microwave radiometer that can measure simultaneously ozone and CO at 110.8 GHz and 115.2 GHz respectively. This radiometer design uses a double side band, Dicke frequency switched receiver [9].

The microwave remote sensing laboratory at the Naval Research Laboratory, DC headed by Dr.Gerald Nedoluha and Mike Gomez, hosts a suite of radiometers that are fixed instruments operational at Mauna Kea, Mauna Loa and Lauder, New Zealand that continuously observe stratospheric constituent molecules such as water vapor [10], ozone and chlorine monoxide (ClO) which is vital for understanding the ozone catalytic cycle. While at NRL, I visited the microwave remote sensing lab and learnt about various aspects involving the ozone and the ClO radiometers. Currently there are no ground based portable *campaign* instruments in the United States that can observe W-band species such as ozone, CO to name a few.

Radiometry concepts:

A radiometer is a thermometer that measures the brightness temperature in its field of view. The physical realization of a radiometer consists of several modules mainly the frontend that includes the 1) antenna, the associated optics and calibration hardware and 2) the heterodyne receiver where filtering, amplification and translating to a lower intermediate frequency (IF) takes place and 3) the backend that is the multichannel spectrometer.

Building and operating a radiometer involves various aspects 1) designing and building a low noise microwave receiver 2) designing the optics 3) programming the spectrometer and 4) finally getting altitudinal profiles using retrieval algorithms.

a) Antenna and optics:

One of the important modules in a radiometer that precedes the heterodyne receiver is the antenna and associated optics. Optics help redirect and transform the beam whereas the antenna couples the microwave energy propagating in free space into the device. The intent is to design optics using quasi-optical techniques to collect the maximum amount of radiation from the target while keeping radiation from extraneous sources to a minimum. Optics have to switch the beam between the atmosphere and the calibration targets. Calibration is done to relate the measured radiometric output (counts or voltage) to brightness temperature units. Hence calibration targets are needed to establish an accurate temperature reference. A variety of plane parallel and curved mirrors are employed to transform the beam size and direction prior to entering the horn antenna and the calibration targets.

The optical design process involves optimizing various parameters such as location, size etc. of the reflective components to minimize the spillover loss. Spillover losses occur due to radiation illuminating beyond the rim of the optical component. A Gaussian beam treatment is typically used for propagating sub-mm or mm wave radiation since ray optics do not work well when the wavelength is on the order of the aperture size.. An example of a modern antenna is the ultra-Gaussian corrugated horn (manufactured by Thomas Keating) antenna that has significantly low sidelobes (~ -40 dB) compared to a standard scalar horn (sidelobe levels ~ -25 dB). The signal radiation from the intended target is maximized by reducing errors due to coupling from unwanted sources.

b) Downconverter module:

The downconverter module selectively amplifies the incoming weak signal received by the antenna to a suitable level required for the backend. After amplification, the RF signal is translated to a lower intermediate frequency signal. This conversion is done by heterodyning or mixing the high frequency, weak RF signal with a fixed frequency strong reference from a local oscillator (LO). The mixing operation is nonlinear resulting in a set of sum and difference frequencies of the RF and LO signals. The advantage of operating at lower down-converted frequency or intermediate frequency (IF) is components such as filters and amplifiers are less expensive and easily available. Further filtering and amplification takes place at the IF stage. When operating as a single sideband receiver, only the difference frequency component is considered. Receivers can be designed to have 1 or 2 IF down-conversion stages. The following figure shows the various components of a typical heterodyne total power receiver.

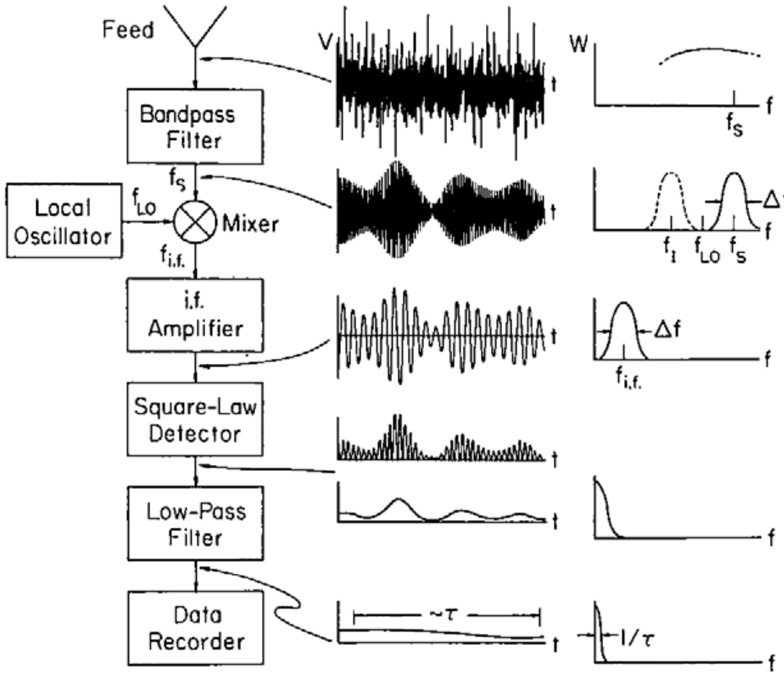


Fig. 3: Total power receiver [11]

The block diagram shown in figure 3 is a total power radiometer system [11]. Radiometers can also be operated in a "Dicke switched" mode where the signal noise power is compared to a reference noise source by rapid switching. Dicke switching is commonly used to overcome fluctuations due to gain instabilities. The amplifier is the dominant source of such instabilities where the gain exhibits variations over the measurement time period leading to fluctuations in the measured brightness temperature.

c) Backend: spectrometer

The traditional spectrum /network analyzers are of the sweeping type where a specified bandwidth is swept or scanned sequentially, frequency by frequency [12]. For accurate observation of lineshapes, sufficient spectral resolution (~tens of KHz) is required. It is impractical to employ traditional spectrum analyzers where only a single frequency would be recorded at a given time out of thousands of datapoints needed to resolve the lineshape. The rest of the data is being ignored while acquiring this single frequency point. To do time averaging to extract weak signals, acquisition time becomes prohibitive, time dependent variations in signal will be exacerbated and instrument drift will obscure the signal.

For radio astronomy and atmospheric observations, it is routine to employ a real time multichannel spectrometer that would give enough bandwidth for narrow lines. Older systems that employed filterbanks and acousto-optical spectrometers (AOS) continue to be replaced with more modern field programmable gate array (FPGA) based spectrometers that implement the fast Fourier transform (FFT) algorithms in realtime.

d) Calibration

The output of the radiometer is expressed in terms of voltage or digital counts (digital spectrometer). In order to relate the voltage or raw counts to an equivalent brightness temperature, the receiver is calibrated using a hot and a cold target. Calibration isolates the measured noise power from the target by removing the contribution due to the inherent noise in the receiver. Choice of a suitable reference include calibration targets that mimic a blackbody source i.e. emissivity very close to 1. Typically microwave absorbers are used in conjunction with a hot or cold reference loads. A load at ambient temperature constitutes the hot load. Sky or a cryogenic load such as LN2 bath is the common choice for a cold load. Assuming that the radiometer follows a linear relationship, the calibration constant can be determined by measuring the output from both the hot and the cold loads. The drawback of using LN2 is that it requires replenishing the bath on a timely basis. Alternately, GROMOS-C uses peltier devices as cold calibration targets for long term unattended operation.

The choice of the calibration target also dictates the engineering design of the receiver and the antenna optics. Temperature uniformity i.e any gradients within the ambient and the cold targets could give rise to standing waves which would manifest as baseline errors in the measurement. Recent success from a 3D printed water based calibration target demonstrated by the THz group in IAP Bern shows promise and potential use in ground remote sensing instruments [13]. There is a need for accurate calibration targets or brightness temperatures standards. The calibration is not considered absolute as there is a lack of a standard or a true reference. This is an avenue where more options can be explored. Perhaps a perfect absorber using artificial materials known as metamaterials [14] could be used as a cold load to calibrate the radiometers.

e) **Retrievals**

In order to extract the concentration information from the measured brightness temperature observations, two key steps are involved [15]. First is the forward model and secondly, the inverse model. The forward model simulates the radiative transfer along the path between the radiometer and the atmosphere with known physical attributes of the atmosphere. Radiative transfer theory describes the microwave interaction of various gas species and includes the contribution due to emission from various atmospheric constituents by using the aforementioned Planck spectral brightness as well as the attenuation along the path between the instrument and the atmosphere. This simulated spectrum using the forward model is then used in an inversion algorithm based on Rodger’s optimal estimation theory [16] to infer the input (concentration as a function of altitude) by using the output (measured brightness /brightness temperature as a function of frequency). The process can be described as an iterative estimation process using initial guesses and finding a solution from a large number of solutions by introducing suitable constraints. The initial guesses are the *a priori* conditions or constraints in order to arrive at a reasonable solution. Instrument errors are often diagnosed by examining the results of the retrieval process.

Microwave remote sensing capability at LANL with suggested improvements

In order to innovate, a foundation needs to be established in microwave spectroscopy to be able to identify potential pathways for improvement. The innovation is not in the instrument itself, but the application. Passive microwave radiometers require accurate *a priori* (valid guess to fitting) data to determine the concentration of the gas species from the measured brightness temperature. In order to achieve a microwave remote sensing capability at LANL, an investment must be made to acquire or construct the needed components of the radiometry system. Due to limited expertise and funding, focus was placed on developing a W-band receiver which could be used for passive measurements independent of a high-power source or bistatic configuration from the proposal.

So far the focus has been towards detecting a greenhouse gas such as ozone but the technology can be translated to other frequencies for studying gases other than ozone. Passive detection for such pollutants would involve similar highly sensitive receiver designs albeit at different frequencies. The specific gas species of interest would dictate the hardware design, including the frontend building blocks of the antenna and optics and the calibration targets and the FFT spectrometer.

If LANL were to focus on building a radiometer suitable for measuring ozone abundances in the stratosphere, the instrument would have to be built to a quality that would be at par with or exceed the performance of current instruments worldwide that measure short to long term trends in ozone.

It is appealing to have a portable radiometer thus lightweight and rugged, requiring infrequent manual intervention. The radiometer would be exposed to the variable environment outside hence the need for hardening. Current radiometer technology is still a R&D effort. Institutions worldwide are pursuing technical innovation alongside building, operating, and maintaining new and existing radiometers. Innovation efforts focus on replacing older components with room temperature and low noise MMIC based technology components. Per discussions with Mike Gomez from NRL who is an expert in microwave radiometry, there is a need for a noise diode that shows a flat response near 110 GHz. This is an avenue worth exploring. The idea of a cold target using a perfect metamaterial absorber could be explored. Other focus areas include spectrometer performance characterization to iron out issues due to nonlinearities that show up as baseline errors in the measurements.

Proposed radiometer design

I propose a preliminary design of a microwave radiometer based on the various modules described earlier. The radiometer is designed to detect the 110 GHz emission line of the atmospheric greenhouse gas ozone. The various modules addressed in this section are the 1) horn antenna, 2) downconverter /low noise receiver, 3) spectrometer backend and finally the data product that is the retrievals.

What we have	What we need
Low noise amplifiers WR-10	Ultra-Gaussian Horn antenna from Thomas Keating, UK
USRP X310 FFTS	High pass filter for RF signal frequency
Balanced WR-10 mixer	Optics and software to optimize beam path
	Calibration targets
	Local oscillator that is frequent stable and has low phase noise PLDRO
	Various IF components
	Temperature stabilization
	Switching components if Dicke switching mode of operation is desired
	Dedicated personnel for assistance with building RF modules, rewriting FFTS firmware and data acquisition etc. and also atmospheric scientists to help with data interpretation and analysis.

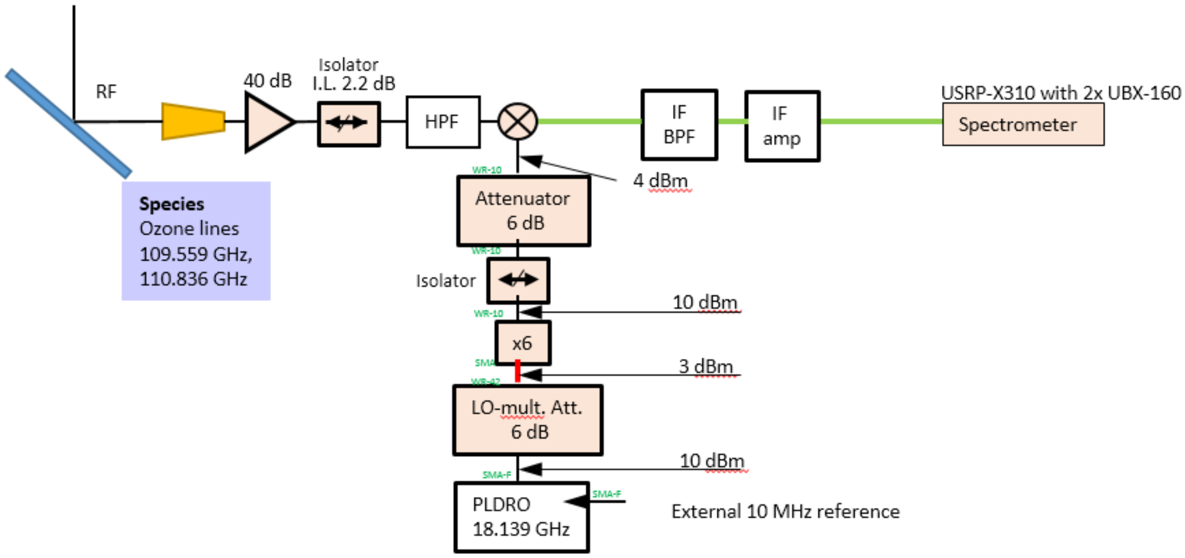


Fig 5: A preliminary design of a total power radiometric receiver

Antenna: As shown in the receiver layout in fig. 5, a horn antenna receives the radiation from the atmosphere over a narrow beamwidth. I propose the use of an ultra-Gaussian horn antenna from Thomas Keating. The coupling efficiency to the main lobe for this horn is high and the sidelobes are very low below -40 dB. The standard scalar horns and the parabolic dish feeds do not have these characteristics in terms of efficiency, beamwidth and sidelobe levels [16]. As the radiation from the atmosphere is weak, it is best to eliminate as many sources of error as possible. Using a state of the art, antenna such as the ultra-Gaussian corrugated feedhorn would help reduce them.

Downconverter: This weak signal is then amplified by the low noise amplifier (LNA) that has a gain of 40 dB. The LNA in the receiver block diagram shown below is Sage SBL-7531144050-1010-S1 with noise figure of 3.5 dB at 110 GHz or an equivalent noise temperature of 328 K. An isolator follows the LNA to prevent any backward propagation. This room temperature receiver design is implemented using WR-10 (75-110 GHz band) waveguide components. The LO chosen for the above design is a phase locked dielectric resonator oscillator (PLDRO). PLDROs are characterized by low phase noise and good frequency stability. The LO arm can be implemented in various ways: 1) using a nominally high fixed LO frequency close to the RF signal frequency. A variation to this design would be to incorporate a tunable LO in order to access neighboring spectral lines for example Ozone at 110.836 GHz and CO at 115.871 GHz , 2) using a much lower frequency LO in conjunction with a multiplier . Sub harmonic mixers allow the use of lower frequency LOs with the tradeoff of a higher conversion loss. This eases the power and the cost requirements by quite a bit. Balanced mixers on the other hand offer better performance at the expense of using higher frequency LOs. The mixer of choice for the design in fig. 5 is an externally biased balanced mixer by Sage millimeter, SFB-10-E2**.**

Backend: Published results show that the performance of fast Fourier transform spectrometers (FFTS) exceeds those of the AOS when parameters such as linearity, stability, frequency drifts are taken into consideration [17]. Agilent's AC240, U1080A and U5303 (Keysight, formerly Agilent) are some of the fast digitizers employed in the radiometers at NRL, DC and IAP, Bern. A software defined radio FFTS from Ettus USRP X310 is a low cost solution for the radiometer backend. Unlike traditional radios, a SDR is reconfigurable. This system is currently on hand in EES-14. The USRP X310 unit uses a Kintex 7 FPGA (Field Programmable GateArray) and an ADC with a sampling rate of 200 MS/s and a 14 bit resolution or 16384 channels. It supports IF signals from DC – 6 GHz with a bandwidth up to 120 MHz. Thus the available spectra resolution is roughly 20 kHz. The bandwidth and the frequency resolution of the spectrometer set the lower and upper limits respectively on the usable altitude range. Combining two or 3 daughterboards (~120 MHz each) would increase the total bandwidth.

Retrievals: During my visit, I learned that the atmospheric scientists at IAP, Bern use a radiative transfer code called ARTS in conjunction with a matlab package called QPACK to simulate the atmospheric radiative transfer i.e. the forward model and compare with the measured spectra.

Conclusion

The scope of microwave radiometry project greatly exceeds the LDRD proposal budget. As shown in the multiple modules that comprise the system, each step is heavily involved and would require investing in equipment, time and manpower. It would best for LANL to collaborate with existing groups that have already developed the expertise.

Acknowledgements

I would like to acknowledge my sincere thanks to Mike Gomez and Dr. Gerald Nedoluha from Naval Research Laboratory (NRL), Washington DC. Mike Gomez has been a wealth of knowledge from the time I started educating myself about this novel remote sensing technique. I got a chance to visit the microwave remote sensing lab at NRL in June 2017 and see some of their instruments. I had various discussions with both Mike Gomez and Dr. Gerald Nedoluha who once again patiently answered my "basic and naïve" questions.

I would like to extend my sincere thanks to Axel Murk and his team in IAP, Bern specifically Jonas Hagen, Martin Lainer, Miko Kotiranta, Franziska Schranz to name a few, for giving me the opportunity to visit the radiometry lab and see a variety of instruments first hand. They were provided invaluable technical feedback.

I would like to thank the LDRD committee for funding this ER proposal. Two years ago, I had no idea that such a field existed. I have now gained considerable knowledge about this technique with email exchanges with the experts in this field and site visits to their labs.

Lastly, I would like to thank my mentor in EES-14, Dr. Brent Newman for being supportive of my initiative to explore microwave radiometry.

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Appendix

This is the proposed budget for the preliminary design of the110 GHz downconverter receiver module. This budget may need to be revised based on alternate components, price and availability updates. The budget would also need to include costs that involve various other components such as the optics, temperature stabilization hardware, hardware related to calibration etc. and also time and labor costs of dedicated team of personnel.

RF		
Corrugated or Ultra Gaussian feedhorn + optics	3 months	\$6000 - 7500 + VDI routing
LNA (20 or 40 dB), Sage SBL-7531142040-1010-E1, (20 dB, N.F at 110 : 5.5) Sage SBL-7531144050-1010-S1 (40 dB,N.F at 110 : 3.5)	On-hand	\$4350
W-Band high pass filter (I.L too high???)	1.5 months	\$1800
W-Band Faraday Isolator Sage STF-10-S1 , I.L. 1.5 – 2.2 dB	Stock	\$995
LO		
PDRO – Ultra Herley 18.139 GHz	3 months	\$1950 to \$2,700
WR-42 to SMA adapter (PENDING) Fairview (I. L. ??)		\$431
Active Multiplier (x 6) :Millitech AMC-10-RFHB0	60 days ARO when not in stock	\$4975
LO path : W-Band Faraday Isolator Sage STF-10-S1 , I.L. 1.5 – 2.2 dB		\$995
Vectron or Wenzel CLOCK		\$1060

STA-30-10-M2 Level Setting Attenuator, W Band – 0 to 30 dB		$720
Balanced Mixer: Sage SFB-10-E2 , Conv. Loss: 10-14 dB,DC to 35 GHz, LO power 3 dBm	On-hand	$3,450
IF		
IF amp, (Minicircuits components) on hand		$ 565
IF filter		
FFTS : SDR Ettus USRP X310 and 2 x UBX-160 (DC-6 GHz)	On-hand	$9490
Running total		$ 45,000